The Science and Strategy for a Long-Baseline Neutrino Experiment Near Detector

Presented to the LBNE Reconfiguraton Steering Committee

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Abstract

Author: Milind

In a previous note (*need a reference*), it was argued that the defining characteristic for the Long-Baseline Neutrino Experiment (LBNE) is the length of the neutrino baseline. All other issues: the depth of the detector, the type of detector, the scope and strategy of the near detector, although important, do not define the nature of the project since they can be enhanced or changed later. This and the prospects for the long term program of neutrino science has resulted in a preference for the option in which a far detector is sited at the Homestake site, 1300 km from FNAL, and a new beamline with the ability to handle power levels of 2 MW or above is constructed.

The financial constraints imposed on the LBNE project do not allow construction of a full near detector complex in the preferred scenario. The near detector could be constructed if resources other than the DOE HEP come into play. In this note, we examine strategies to maintain the initial scientific performance without a full near detector complex. Although detailed evaluation must await full simulations, it is our conclusion that ....

If you would like to contribute to this document, please contact Sam, Mary, and Christopher.

I. OVERVIEW AND PURPOSE

Authors: Sanjib, Milind, Sam

With the discovery of non-zero θ_{13}, the next generation of long-baseline neutrino experiments offer the possibility of obtaining a statistically robust spectrum of muon and electron neutrinos and anti-neutrinos with large oscillation effects. Such measurements are scientifically well-motivated and well-appreciated as a unique capability in the U.S. Such long-baseline neutrino physics should remain a key objective in any phasing or reconfiguration plan that aims for U.S. leadership at the Intensity Frontier.

In such long-baseline neutrino oscillation experiments, one searches for alterations in the composition of a neutrino beam as it propagates from its source to a Far Detector (FD) hundreds of kilometers away. The search broadly comprises three distinct but overlapping tasks. First, one must characterize the instrumental response of the FD to a neutrino interaction. This includes having detailed knowledge of final state particle multiplicities and kinematics - quantities that will be used to infer the incoming neutrino energy. Second, one must thoroughly characterize the beam at the source to properly account for potential differences in the beam between the source and FD. Third, in order to cleanly detect the oscillation signal and any accompanying neutrino/antineutrino differences, one must determine the prevalence and provenance of background events in both neutrino and antineutrino running. All three of these tasks are duties of a Near Detector (ND) complex.

The LBNE collaboration put forth a proposal for a 34 kt liquid argon (LAr) detector sited underground at the Homestake mine in South Dakota ($\sim$1300 km from Fermilab) and a smaller LAr TPC in conjunction with a very high resolution tracker as its ND. Budget constraints have since induced LBNE to proceed in phases. Three possible options for phase-I of LBNE were identified by the LBNE Reconfiguration Steering Committee:

1. 10 kt LAr TPC on the surfacce at Homestake (1300 km) and a new neutrino beam
2. 15 kt LAr TPC underground at Soudan (735 km) using the existing on-axis NuMI beam
3. 30 kt LAr TPC on the surface at Ash River (810 km) using the off-axis NuMI beam

The "preferred option", recommended by the project and the LBNE Reconfiguration Steering Committee, calls for (1) a 10 kt LAr TPC on the surface at Homestake and a new neutrino beam. The choice abridges two crucial features of the LBNE science program, the underground physics and a rich ND program. Nevertheless, the first phase offers a chance to discover the neutrino mass hierarchy (MH) and to detect CP violation in the neutrino sector. The current document therefore outlines a strategy for beam-related neutrino oscillation measurements with a minimal ND in phase-I which aims to be consistent with budgetary constraints while providing sufficient systematic precision in characterizing the neutrino source and backgrounds for the MH and CP measurements. Note that this strategy and its associated costs can be different for the NuMI vs. Homestake options, as a near hall and detectors already exist (or will exist) for the NuMI options.

In this, note we first describe the analysis issues in a long-baseline experiment. We then calculate the signal and background event rate expected for the Homestake and NuMI options. A brief review of previous experimental experience is followed by a number of possible options for LBNE for the initial phase of running. The options considered take into account the financial constraints that have been discussed in the FNAL Reconfiguration Steering Committee. These constraints do not allow the fully envisioned near detector complex and associated civil construction as described in the LBNE conceptual design report to be available in the first phase.

II. SYSTEMATIC PRECISION IN PHASE-I

Authors: Sanjib, Sam, Elizabeth, Zeynep

Figures 1–3 show the expected spectrum of ν_e charged current (CC) events in a 34 kt FD at the Homestake and NuMI sites, in both neutrino and antineutrino modes for normal and inverted mass hierarchies. Corresponding event rates are available in the appendix. The three dominant beam-induced backgrounds are from (a) neutral-current (NC) events, where a π^0 produced in the hadronic shower mimics a signal-like ('prompt') electron shower, (b) ν_μ CC interactions, where the outgoing muon is mistaken as an electron, and (c) intrinsic, irreducible beam ν_e events. All three backgrounds contribute approximately equally in the relevant energy range (0.5-8 GeV) although the NC background dominates at lower energies and the intrisic ν_e background is fractionally a bit larger for Ash River than for the other options. The complete LBNE proposal stipulated a systematic error of 1% on ν_e backgrounds and 5% on NC and ν_μ CC backgrounds, justified by ND studies. In Phase-I, however, the large reduction in the FD mass causes the statistical error to dominate over the assumed systematic error in the ν_e appearance analysis for the first few years of running. Figure 4 shows how the statistical uncertainty on the appearance signal in both neutrino and antineutrino modes evolves in time. With the assumed (reduced) detector masses, the appearance measurements will be at the level of a 5-6% (8-10%) statistical error in 5 years of neutrino (antineutrino) running.

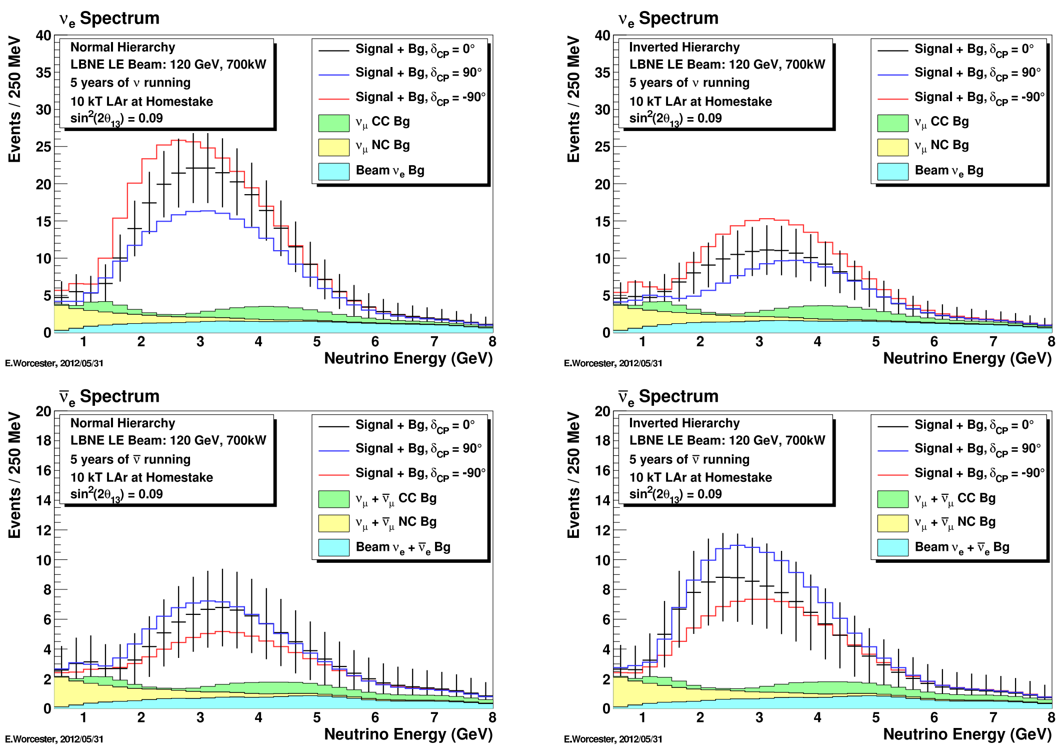

FIG. 1: Expected spectrum of ν_e events in 5 years of neutrino (top) and antineutrino (bottom) running for both the normal (top) and inverted (bottom) mass hierarchies for the Homestake option. The backgrounds induced by NC, ν_μ CC, and intrinsic ν_e are also shown. Plots are compliments of E. Worcester (BNL).

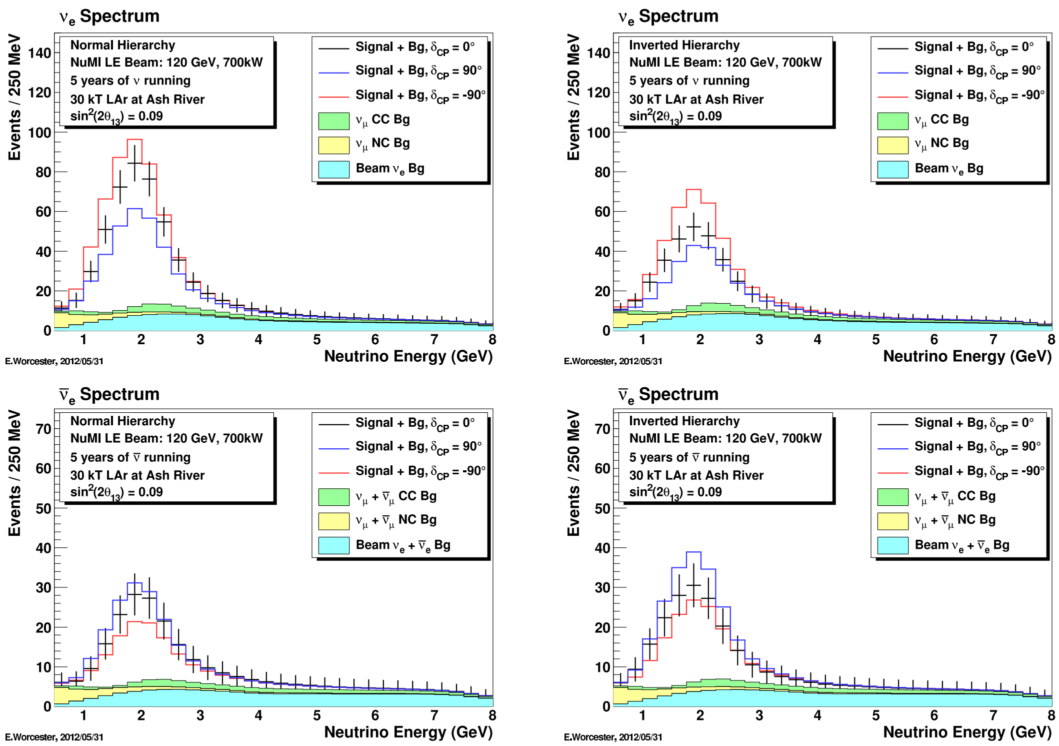

FIG. 2: Same as Figure 1 except for the Ash River option.

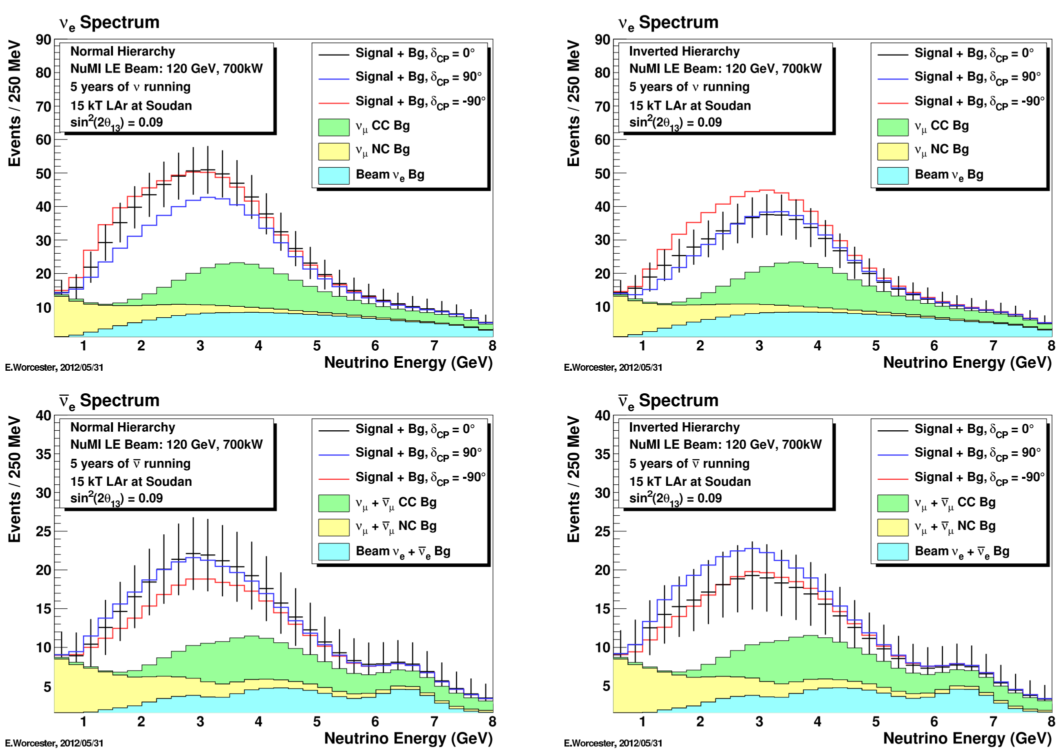

FIG. 3: Same as Figure 1 except for the Soudan option.

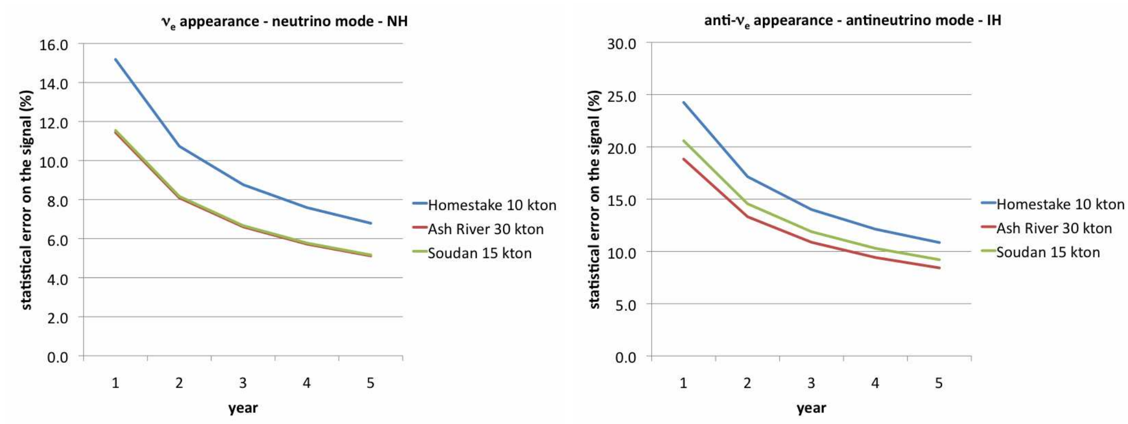

FIG. 4: Evolution of the statistical error on the appearance signals in time for both neutrino (left) and antineutrino (right) running. The highest statistics case is plotted in each case, meaning the normal mass hierarchy for neutrinos and the inverted mass hierarchy for antineutrinos. Signal rates are for $\sin^2 2\theta_{13} = 0.09$ and $\delta_{CP} = 0$ (see Appendix). *Need higher resolution plots.*

For the reconfiguration options, the statement that the statistical error will likely dominate in the appearance measurements assumes that (a) we can reliably estimate expected systematic uncertainties without a full near detector complex and (b) we can estimate the overall background level and energy-dependence in a LAr TPC. Such background expectations have so far been evaluated by hand scans of simulated events. Hence, a modest ND (or LAr TPC operating in a similar energy range) that provides a means of measuring mis-identification rates and spectra in LAr would be very valuable, even in this statistically limited scenerio.

Given current background estimates for LAr, Figure 5 shows the effect of increasing the uncertainty on the signal and background normalization uncertainties for the mass-hierarchy and CP violation measurements in LBNE. These are the results from a simple GLoBES-based study where only the normalization on the signal and background are varied, assuming their energy spectrum is known. For Phase-I, the exacerbation of the normalization uncertainties from 5% to 15% for backgrounds and from 1% to 5% for signal events is smaller than, for example, the full 34 kt FD where the statistical precision demands better systematic determination of both signal and background. Therefore, given the smaller FD masses, we may be able tolerate larger systematics in phase-I.

The sitiuation is quite different for the disappearance measurements. There, the anticipated signal is naturally much larger than for the appearance measurements and hence the statistical uncertainties are much smaller. Figure 6 shows how the statistical uncertainty on the disappearance signal evolves in time. With the assumed (reduced) detector masses, the disappearance measurements will be at the level of a 0.8-2.0% (1.1-2.8%) statistical error in 5 years of neutrino (antineutrino) running, depending on the baseline. Obviously, with the shorter baseline for Soudan, the overall statistics are much larger and hence the statistical errors are smallest in that case. For all of the phase-I options, the increased statistics expected in the disappearance channel and the need to very accurately measure distortions in the observed ν_μ and $\overline{\nu_\mu}$ spectra, thus make the need for ND measurements more pressing if we are to improve the accuracy with which we know Δm^2_{23} and θ_{23} by the time of LBNE.

Having established that the level of systematic uncertainty required in phase-I of LBNE will be different for the appearance and disappearance measurements, the next section will summarize the level of precision that has been achieved in prior experiments that have conducted neutrino oscillation searches and the techniques that have been used to achieve that precision.

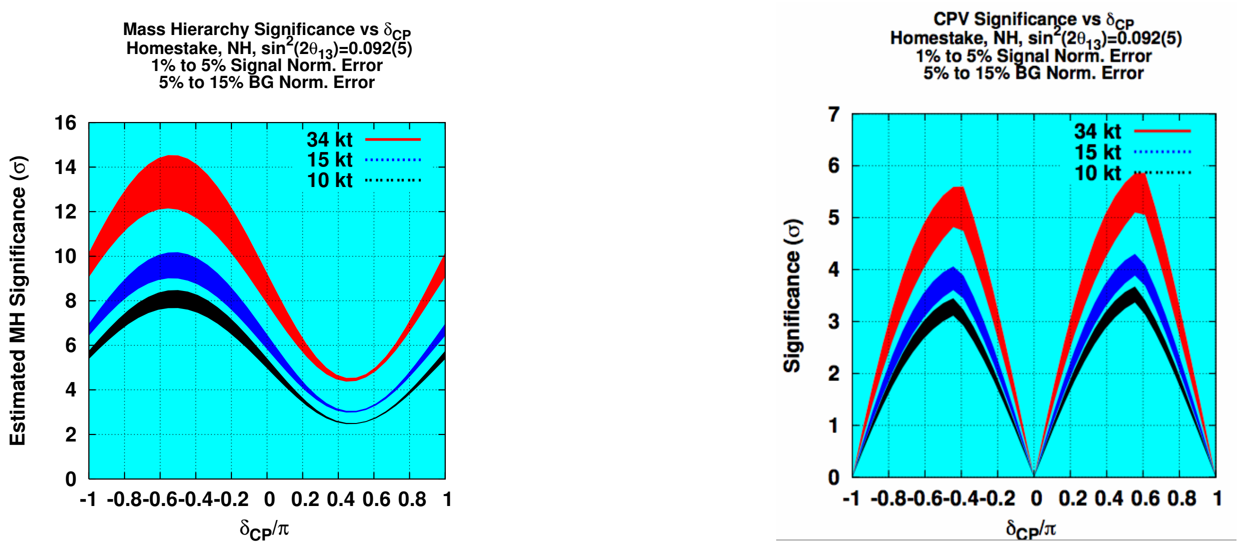

FIG. 5: Mass hierarchy (left) and CP violation (right) sensitivity for a range of assumed background and signal normalization errors for a 10, 15, and 30 kt FD at Homestake. In this study, the shape of both the signal and background events are assumed to be perfectly known. Plots are compliments of M. Bass (CSU).

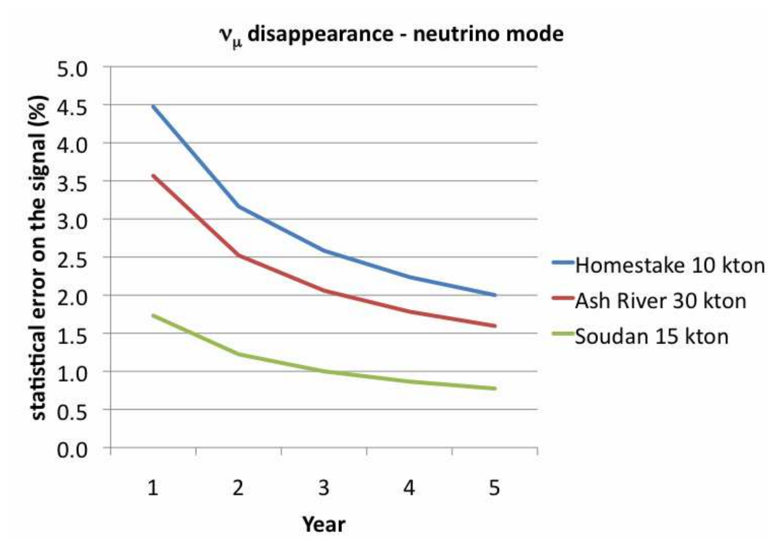

FIG. 6: Evolution of the statistical error on the disappearance signals in time for both neutrino (left) and antineutrino (right) running. Signal rates are for oscillated events assuming $\Delta m^2_{23} = 2.3 \times 10^-3$ eV^2 and $\sin^2 2\theta_{23} = 0.705$ (see Appendix). *Need antineutrino plots and higher resolution versions.*

III. PREVIOUS EXPERIMENTAL EXPERIENCE

Author: Sanjib

Past searches for $\nu_\mu \to \nu_e$ oscillations at large Δm^2 (short-baseline) include E776 in both narrow- and wide-band beams [**?** **?**], MiniBooNE [**?**], NOMAD [**?**], MINOS [**?**], etc. With the exception of MINOS, these were all single-detector experiments with NC π^0 and intrinsic beam ν_eś as the dominant backgrounds. Table I summarizes the overall systematic error in the $\nu_\mu \to \nu_e$ appearance search achieved by these experiments. With the exception of NOMAD, none of these experiments had a resolution better than what is expected from a LAr TPC. A brief synopsis of systematic errors achieved by these experiments is given below.

Experiment	NC/CC (π^0) Events	Beam-ν_e Events	Syst.Error	Comment
E776(89)(NBB)	10	9	20%	No ND
E776 (WBB)	95	40	14%	No ND
MiniBooNE	140	250	9%	No ND
NOMAD	<300	5500	< 5%	No ND
MINOS	44	5	5.6%	ND–FD

TABLE I: Summary of achieved systematic error performance in some past $\nu_\mu \to \nu_e$ oscillation experiments. *Table is from Milind, docdb 3648.*

A. E734

Author: Milind

B. E776

Author: Milind

C. MiniBooNE

Author: Sam

D. NOMAD

Author: Sanjib

NOMAD was a low-density ($\rho \approx 0.1$ gm/cm^3) fine-grain tracker. It was designed to search for τ-appearance in $\nu_\mu \to \nu_\tau$ oscillations. Charged particles were tracked by light drift chambers; the electron-ID was achieved by TRD, preshower, and ECAL subdetectors. The tracker and preshower-ECAL were embedded in a dipole B-field (0.4 T). Outside and downstream of the magnet were muon-detectors and an HCAL. The fine-grain tracker originally envisioned for LBNE ND complex, HIRESMNU [**?**], is built on the NOMAD experience. It improves upon NOMAD in electron-ID, charged particle tracking, and provides 4π calorimetric and muon coverage. Because NOMAD could distinguish e^- from e^+ and reconstruct the missing-P_T vector on an event-by-event basis, the π^0-induced background could be kept at a very low level ($\sim 5\%$ in the $\nu_\mu \to \nu_e$ search).

E. MINOS

Author: Zeynep, Mary

F. T2K

Author: Bob W

IV. EXPECTED CONTRIBUTIONS TO SIGNAL AND BACKGROUND UNCERTAINTIES

Author: TBD

V. OPTIONS FOR LBNE

Author: TBD

Options for possible near detector measurements are different for the various reconfiguration choices due to the availability of existing near site resources in some of the cases. Table II summarizes existing (or soon to be existing) near site resources.

configuration	existing ND hall	existing near detectors
Homestake 10 kton	N/A	N/A
Soudan 15 kton	NuMI on-axis near hall	MINERνA, MINOS ND
Ash River 30 kton	NOvA off-axis near hall	NOvA ND

TABLE II: Existing near site infrastructure for the various options.

A. Signal and Background Evaluation with Far Detector Data Alone

Author: Sanjib

As in the previous single-detector $\nu_\mu \to \nu_e$ experiments, the FD itself will provide control data samples which will help further constrain π^0 backgrounds and intrinsic ν_e which, after all, come from muon-decays (which in turn comes from pion which are the dominant source of ν_μ CC or $\overline{\nu_\mu}$ CC), and kaon-decays. Finally the atmospheric neutrino-oscillation parameters ($\nu_2 \to \nu_3$) will have been well measured by the NOνA and T2K experiments. Using the precisely known θ_{23} and Δm^2_{23}, and using the FD ν_μ and $\overline{\nu_\mu}$ CC data, one can extract further constraints on the neutrino flux.

B. Techniques Using External Measurements

Author: Mary

C. Placement of a Surface Detector in the LBNE Beamline

Author: Sanjib

We assume that Phase-1 of LBNE will have the following features.

1. 10 kt LAr at Homestake, at 1300km from Fermilab

2. run for 3+3 years in neutrino and antineutrino modes

In neutrino mode, for $\delta_{CP} = 0°$, the expected number of signal events for the normal mass hierarchy is $\sim$200 and the expected number of background is $\sim$80 events (see Appendix). In antineutrino mode, the corresponding number of signal events is $\sim$ 60 and the number of background-events is 40. For $\delta_{CP} = -90°$ ($+90°$), the number of signal goes up (down) by $\sim$ 40 events; the background remains unaltered. In the energy range, $0.5 \leq E_{\rm vis} \leq 8$ GeV, the three sources, NC, ν_μ CC, and beam ν_e contribute equally to the background – the NC events contribute more at the lower energy end, while the CC events more above the first oscillation maximum. The statistical error of the (200+80) events is 16. Therefore, so long as the systematic error of the background ($\sim$80 events) remains much smaller than 16, the quality of the MH and CP violation sensitivities will not suffer. Therefore, the task for the ND in phase-I of LBNE is to measure the three backgrounds with a precision of $\sim$ 15%.

The ND must measure π^0 from NC and ν_μ CC interactions at $E_\nu \sim 2.5$ GeV. The least expensive, and the easiest option, is an LAr-ND on the Surface (LBNE-NDoS). We propose to put an existing LAr detector on the surface of the LBNE beamline; for example, the 35 ton detector under consideration could be placed atop the absorber-hall. Such an on-surface detector is operating in the NOνA project (NOνA-NDOS). Figure 7 shows the ν_μ spectrum originating from the NuMI beamline in the NOνA-NDOS. The ν_μ from π^+ (blue-histogram) and K^+ (red-histogram) exhibit distinct Jacobean peaks. Figure 8 shows the corresponding $\nu_\mu$spectrum originating from the new LBNE beamline for the detector on the surface. The shapes of the ν_μ spectra in the NDoS are similar in the NuMI and LBNE beamlines. Given the resolution of LAr detectors, it is clear that LBNE-NDoS will well measure π^0 production in the energy range 0.5—5 GeV. Furthermore, as Figure 8 shows that in a 35 ton LAr TPC, there will be ample statistics to measure π^0 production in the 2.5 GeV region where the first oscillation maximum occurs. It should be noted that the MicroBooNE detector will measure the π^0 yield in ν-Ar interactions below 2 GeV.

The LBNE-NDoS will be manifestly off-axis, exhibiting neutrino spectra different from that observed by the LBNE far-detector. for example, the NOνA-NDOS cannot measure the NuMI neutrino-spectra in the FD in MINOS or NOνA. Figure 9 shows the combined ν_μ and $\overline{\nu_\mu}$ spectra in the on-axis MINOS-ND before and after tuning the π^+/K^+ production cross-sections to the observed neutrino data in the MINOS-ND. The spectra are different from the NDoS spectra because on- and off-Axis detectors sample different kinematic phase space (P_z versus P_T) of the π^+/K^+ decays. The on-axis re-weighting for π^+ and K^+ in the P_z and P_T plots are shown in Figure 10, as gleaned from the MINOS-ND analysis. The NuMI-based detectors at the near site, however, (MINOS-ND, NOνA-ND, and NOνA-NDOS) provide us with a suite of measurements to project the on-axis flux in LBNE using the off-axis spectra. Additionally, at the NuMI near site, the MicroBooNE detector (off-off-axis) will have been operational for several years providing further constraints. Finally, one has the charge-separation in the MONOS detectors, ND and FD, which calibrates the ν_μ vs $\overline{\nu_\mu}$ contamination in the neutrino beam created by 120 GeV protons.

In summary of LBNE Phase-I, we propose to put an existing LAr detector (LAr-ND) on the surface – possibly the 35 ton detector under consideration, and possibly atop the absorber hall at the end of the LBNE decay-pipe. (A possible concern is the amount of beam-muon impinging the detector at this site.) Such an arrangement will provide the π^0 production in the NC and CC. The suite of NuMI near detectors — NOνA-NDOS, NOνA-ND, and MINOS-ND — in conjunction

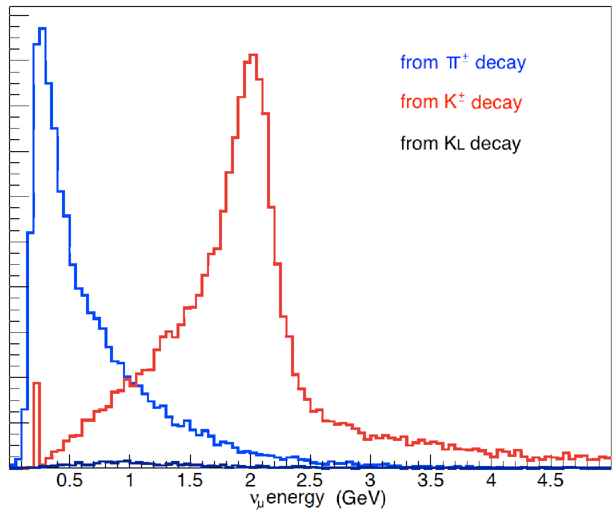

FIG. 7: The ν_μ spectrum in the NOνA-NDOS. The ν_μ from K^+ and π^+ are shown in red and blue histograms. The small K_L contribution convey the level of ν_e expected in the NDoS.

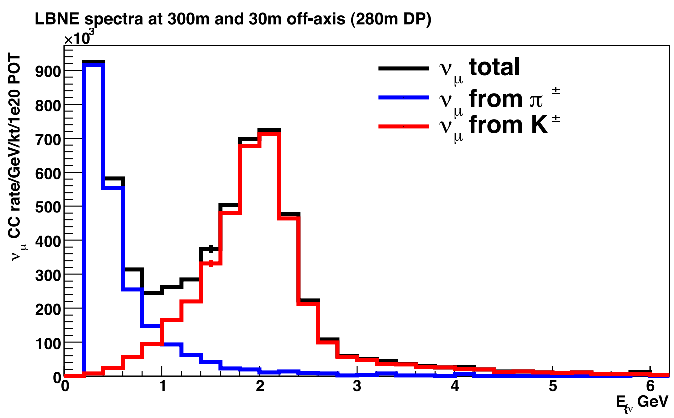

FIG. 8: The ν_μ spectrum, from the LBNE beamline, expected in a surface detector. The Jacobean peaks are rather similar to those expected in the NOνA-NDOS. The figure also conveys that there will be ample statistics in a 35 ton LAr detector.

with the LBNE-NDoS will yield the on-axis LBNE neutrino and antineutrino spectra; and such a strategy will be inexpensive.

1. *The ND Analysis Steps*

We propose to put on the surface, for example above the absorber hall, an existing LAr detector — the 35 ton LAr detector under consideration — for the Phase-I of LBNE. The LBNE-NDoS will yield π^0 measurements in the 0.5–5 GeV neutrino energy region. The off-axis spectrum, however, will be drastically different from the on-Axis spectrum expected at the FD. However, using the set of NuMI near-detectors — NOνA-NDOS, NOνA-ND, and MINOS-ND — an inexpensive and empirical path is laid forward to determine the backgrounds to $\pm15\%$ precision for the MH and CP violation measurements. The salient analysis steps are:

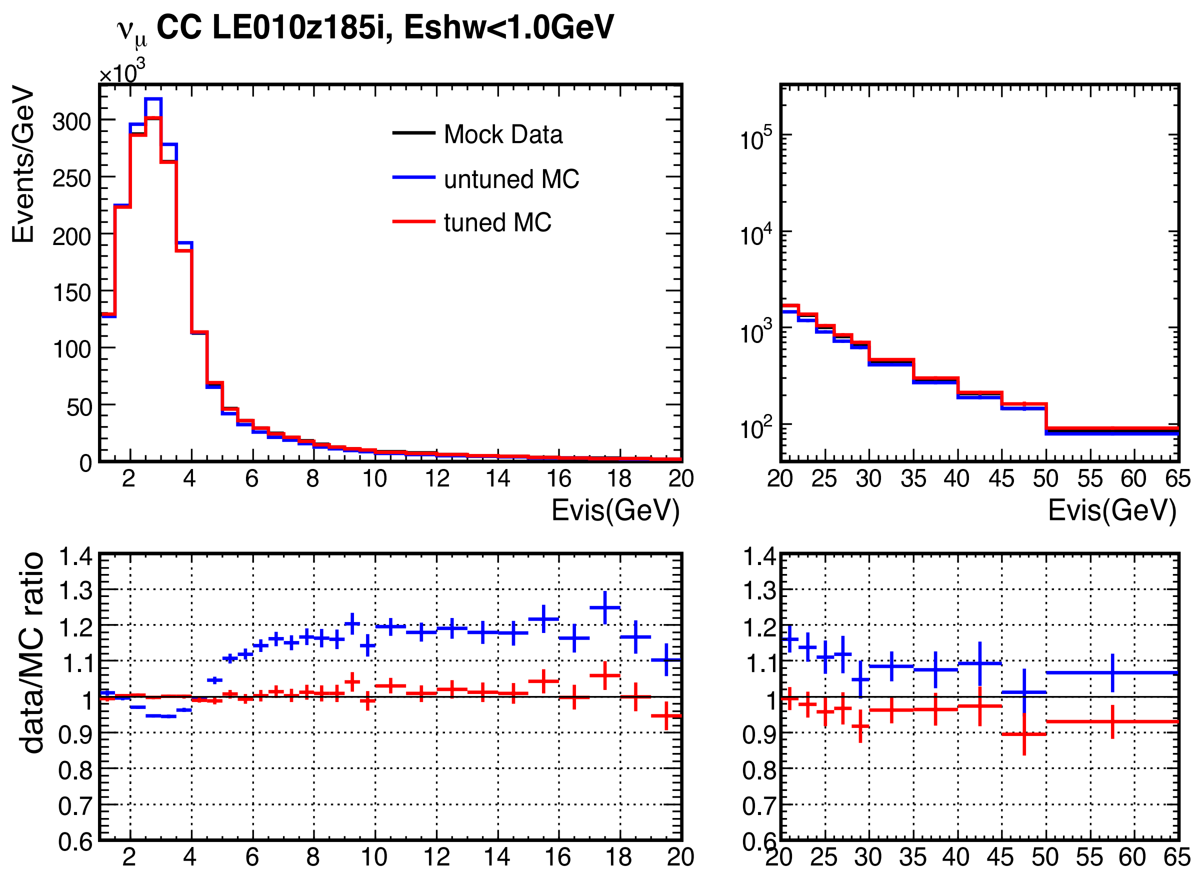

FIG. 9: The ν_μ and $\overline{\nu_\mu}$ spectra in the on-axis MINOS-ND in LE mode.

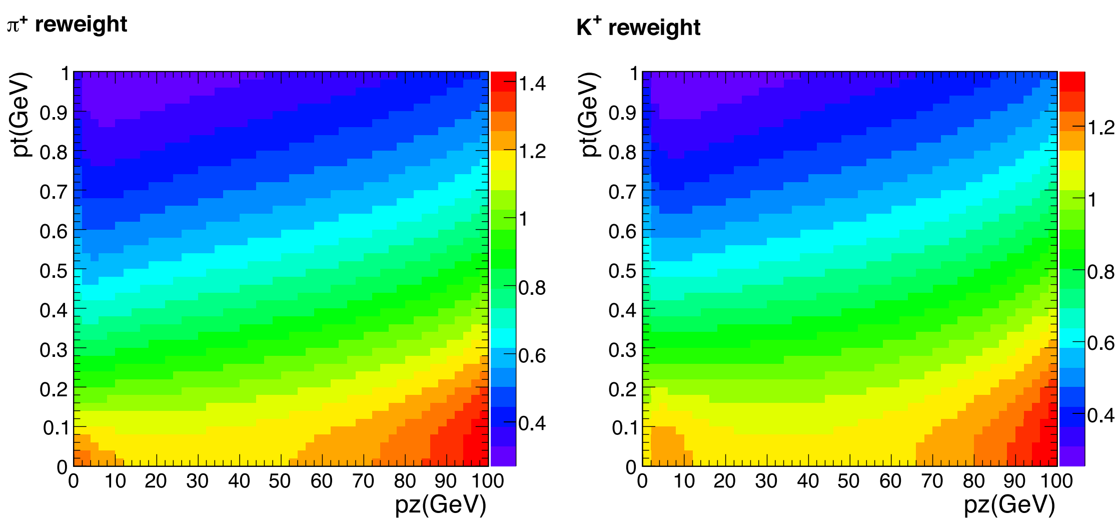

FIG. 10: π^+ and K^+ reweighting as a function of linear and transverse momenta.*Need p_T p_z plots for the LBNE beam.*

1. Measure the neutrino spectra in NuMI-beam line using NOνA-NDOS, MINOS-ND, and NOνA-ND. The MicroBooNE data will provide additional constraint on the off-axis neutrinos and ν-Ar cross-sections below 2 GeV. Finally, the MINOS-FD and NOνA-FD data will provide redundant checks on the neutrino spectra from $\pi^{\pm}$ and $K^{\pm}$.

2. Understand and quantify the on-axis versus off-axis neutrino spectra based upon the set of measurements in (1). This involves π^+/K^+ and π^-/K^- induced spectra (P_z vs P_T) and constraining the K/π yield needed for the ν_e and $\overline{\nu_e}$ predictions.

3. Place the existing 35 ton LAr detector on the surface in the LBNE beamline. The station could be on/near the absorber hall, *i.e.* minimize expense on the conventional facility.

4. Measure the π^0 yield in NC and CC in the neutrino energy range 0.5–5 GeV in LBNE-NDoS. This takes care of the π^0-induced backgrounds in the MH and CP violation analyses.

5. Using the NuMI data, steps (1) and (2), and the LBNE-NDoS obtain the on-axis spectrum in LBNE.

6. LBNE-NDoS will provide K/π, which in conjunction with (2) will yield a measure of ν_e and $\overline{\nu_e}$ in the beam.

7. LBNE-NDoS will measure the small ν_e and $\overline{\nu_e}$ contamination in the beam with a better resolution than the NOνA or MINOS detectors. These events, $\sim$0.6% of the more abundant ν_μ will have a flat energy spectrum, similar to the K_L-induced ν_μś as shown in the Figure. This measurement provides a redundant check of step (6).

8. Finally, control samples in the FD will yield additional constraints on the π^0 backgrounds and the flux (Section V A). The $\nu_2 \rightarrow \nu_3$ oscillations will have been very well measured, and these parameters in conjunction with the ν_μ and $\overline{\nu_\mu}$ CC data in FD will provide constraints on the background for the MH and CP violation measurements.

Although detail estimation must await full simulation, in our judgement the ND-strategy and the analysis outline presented above will adequately constrain the backgrounds for the phase-I Homestake option for LBNE.

VI. FUTURE PROSPECTS

Author: Sanjib

In a new generation neutrino oscillation experiment, such as LBNE, the increased intensity of the beam and the increased scale of the FD will greatly enhance the number of events detected. On the other hand, the discoveries that we seek will be considerably more subtle than in MINOS or NOvA. In these circumstances, the systematic error, especially in regards to phenomena beyond the existing PMNS paradigm, will have to be precisely measured by a the ND complex, as envisioned in the full LBNE proposal, since the ability to constrain systematic error rests squarely on the competence of the ND.

In greater detail, the ND will fulfill four principal goals:

1. It will determine the absolute and relative abundances of the four neutrino species, ν_μ $\overline{\nu_\mu}$ ν_e and $\overline{\nu_e}$ in the LBNE beam as a function of neutrino energy.

2. It will determine the absolute energy scale, a factor which determines the value of the Δm^2 parameter.

3. It will determine the rate of charged and neutral pion production both in NC and CC interactions.Pions are a predominant source of background in both the appearance and disappearance measurements.

4. It will determine neutrino cross sections on argon. Knowing the cross sections at the energies typical of the LBNE beam is essential for predicting both the signal and the background.

Such an LBNE ND complex will perhaps be the most precise neutrino apparatus for cross-sections, electroweak parameters, and new searches attracting contributions outside the DOE.

VII. CONCLUSIONS

Author: All

APPENDIX A: APPENDIX

1. ν_e Appearance Event Rate Tables

Expected signal and background event rates for the ν_e and $\overline{\nu_e}$ appearances measurements in the various LBNE reconfiguration options. The same assumptions about expected signal efficiencies and background rejection are used in each case [1].

configuration	signal	total bkg	ν_μ CC	NC	beam ν_e
Homestake 10 kton, NH	217	79	24	19	36
Soudan 15 kton, NH	375	419	159	81	180
Ash River 30 kton, NH	382	230	49	32	149
Homestake 10 kton, IH	95	79	24	19	36
Soudan 15 kton, IH	207	419	159	81	180
Ash River 30 kton, IH	217	230	49	32	149

TABLE III: Expected event rates in neutrino mode for 5 years of neutrino running at 700 kW (6×10^{20} POT/year at 120 GeV) assuming $\sin^2 2\theta_{13} = 0.09$ and $\delta_{CP} = 0$. Rates are summed from $0.5 - 8$ GeV.

configuration	signal	total bkg	ν_μ CC	NC	beam ν_e
Homestake 10 kton, NH	62	43	12	13	18
Soudan 15 kton, NH	144	237	79	60	98
Ash River 30 kton, NH	130	142	28	21	94
Homestake 10 kton, IH	85	43	12	13	18
Soudan 15 kton, IH	118	237	79	60	98
Ash River 30 kton, IH	141	142	28	21	94

TABLE IV: Expected event rates in antineutrino mode for 5 years of neutrino running at 700 kW (6×10^{20} POT/year at 120 GeV) assuming $\sin^2 2\theta_{13} = 0.09$ and $\delta_{CP} = 0$. Rates are summed from $0.5 - 8$ GeV.

2. ν_μ Disappearance Spectra

Figure 11 shows the expected signal and background rates for the ν_μ and $\overline{\nu_\mu}$ disappearance measurements in a 34 kton FD at the various baseline options. These rates have been scaled to the appropriate reconfiguration masses in Figure **??**. The same assumptions about expected signal efficiencies and background rejection in LAr have been used in each case [1].

[1] T. Akiri *et al.*, arXiv:1110.6249 [hep-ex].

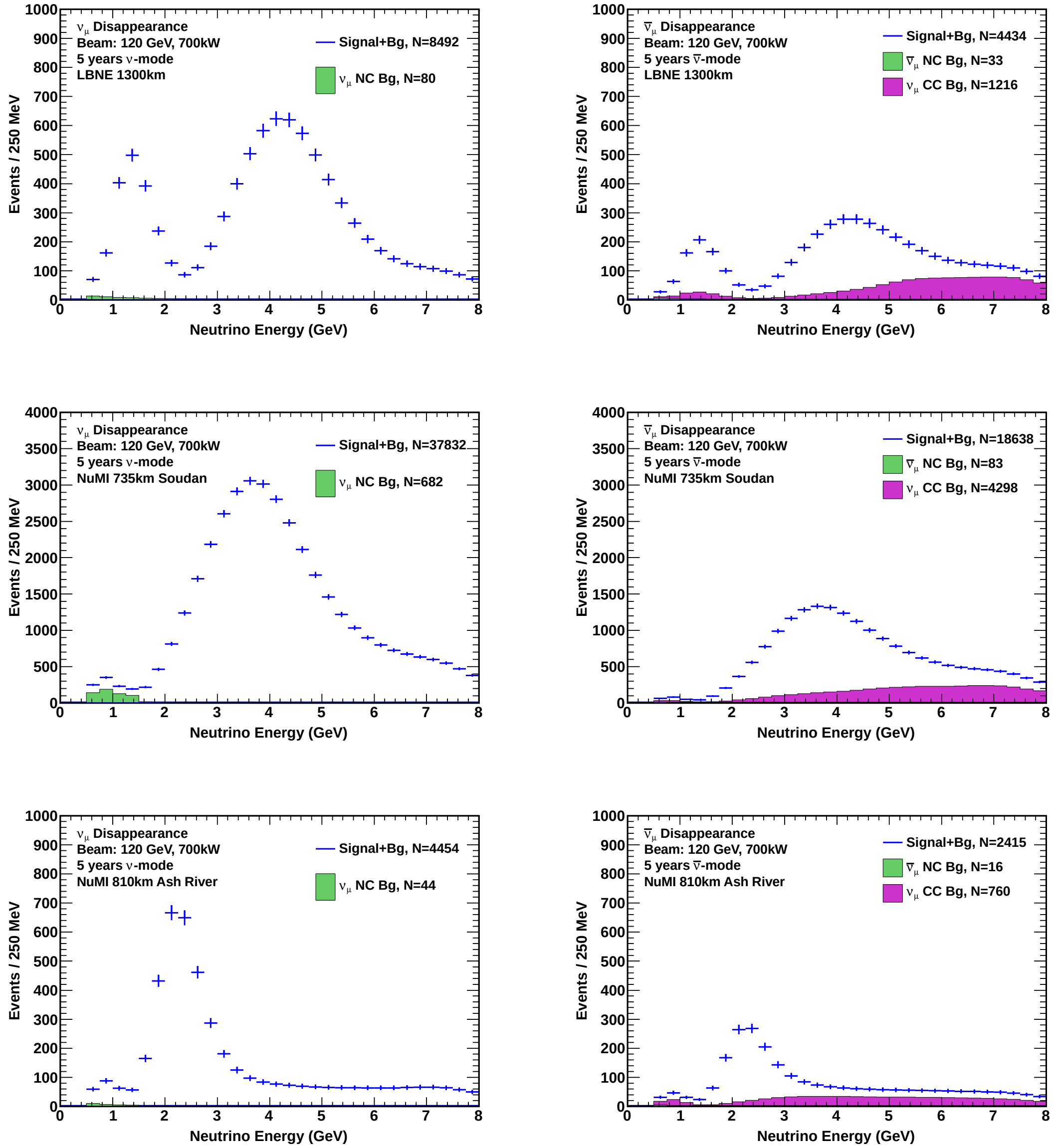

FIG. 11: Expected spectra of oscillated ν_μ (left) and $\overline{\nu_\mu}$ (right) events for a 34 kton far detector at Homestake (top), Soudan (middle), and Ash River (bottom) assuming $\Delta m^2_{23} = 2.3 \times 10^-3$ eV^2 and $\sin^2 2\theta_{23} = 0.705$. Listed event rates have been summed from 0-8 GeV. Plots are compliments of Z. Isvan (BNL).